THE CAS-ECFA-INFN WORKSHOP ON THE GENERATION OF HIGH FIELDS
FOR PARTICLE ACCELERATION TO VERY HIGH ENERGIES: A SUMMARY

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ABSTRACT

The Workshop reviewed several of the various approaches to very high energy linear colliders which are now being pursued. Needed beam parameters were discussed as were the particular characteristics and unresolved problems of these approaches. Most recent experimental data bearing on some of the linac schemes were presented.

INTRODUCTION

Our basic objective is to provide accelerators for pushing back the frontiers of particle physics. The consensus is that this will require accelerators producing "elementary" reactions at energies significantly beyond those now available. For this colliding beams are needed. It is believed that high gradient linear colliders will be necessary, particularly for electrons because of synchrotron radiation. They may also be needed for pp, $\bar{p}p$ or ep where the colossal scale and synchrotron radiation will become dominant features at energies beyond those now planned.

It is likely that sometime in the next decade hadron collisions between beams of 10-20 TeV will become available through use of "standard" accelerator methods. They will provide hadronic "elementary" interactions of 2-4 TeV or more in the center of mass thereby setting the time and energy scale for the needed new technology. Thus the first window of opportunity for a major new facility employing one of the new technologies will be for an $e^+e^-$ machine of approximately 1 TeV beam energy, complementary to the precited hadron collider. To achieve pioneering status on the energy frontier, an $e^+e^-$ machine of 5-10 TeV per beam would be required.
While there are many "ifs, ands, and buts" in consideration of needed luminosity, a conservative approach based on physics we know demands a luminosity of at least $10^{32}\text{cm}^{-2}\text{sec}^{-1}$ for 1 TeV elementary interactions. At least some of the important elementary cross-sections we want to study will decrease as the inverse square of the beam energy so that their investigation at 10 TeV would require a luminosity of $10^{34}$. Accordingly it is incumbent on us to explore the technical and economic consequences of providing such luminosities at the higher energies.

In principle one could explore possibilities for linear colliders for $e^+e^-$, pp, $\bar{p}p$, and ep at multi-TeV energies. At the Workshop we chose to concentrate on $e^+e^-$ colliders for several reasons: no economical way to achieve TeV collisions with these "elementary particles" now exists; at least superficially, multi-TeV $e^+e^-$ interactions promise to be relatively clean; beam energy needed for pioneering work with $e^+e^-$ is about one tenth that required for protons. (Naturally a low cost linac producing more than a few hundred MV per meter would also compete favorably with the synchrotron in acceleration of protons, as has often been observed.)

Our challenge is to find technically feasible means for constructing linear colliders at energies beyond those now achievable. They must produce high luminosity and be more cost effective than current technology.

**GENERAL RULES FOR E^+E^- COLLIDERS**

Independent of the type of accelerator device there are certain basic relations among beam parameters which must be maintained. These put certain engineering constraints on the overall collider design.
The basic particle physics parameters are:

**Beam Energy**  \( \gamma m_0 c^2 \)

**Luminosity**  \( L \text{ [cm}^{-2}\text{sec}^{-1}] \)

(Reaction Rate = L x Reaction Cross-section)

**Fractional Energy Spread**  \( \delta \)

(Accumulated during collision due to "beamstrahlung")

The associated accelerator parameters which influence technical feasibility and cost are:

**Beam Power**  \( P_b \) (power)

**Repetition Rate**  \( f \) (Hertz)

**Bunch Population**  \( N \) (number)

**Bunch Area at Collision**  \( A \text{ [length]}^2 \)

**Disruption Parameter**  \( D \) (number)

**Focusing Parameter at Collision**  \( \beta* \) (length)

**RMS Beam Size at Collision**  \( \sigma* \) (length)

**Beam Emittance**  \( \epsilon = \frac{\sigma^*}{\beta*} \)

**RMS Bunch Length**  \( \sigma_1 \) (length)
For a simple, cylindrical, gaussian beam without pinching or quantum corrections taken into account the basic relations are given below. More general and sophisticated versions of these relations can be found in Refs. 1, 2, 3.

\[ L = \frac{fN^2}{A} \quad \text{and} \quad D = \frac{2\pi r_0 \sigma_0 N}{\gamma A} \]

\[ A = 4\pi \sigma^2 \]

\[ P_b = fN \gamma m_0 c^2 \quad \text{and} \quad \delta = \frac{4\pi}{3\sqrt{3}} \frac{r_0^3 N^2 \gamma}{A \sigma^2} \]

NOTES

1. \( P_{AC \text{ total}} = \left( P_0 + \frac{P_b}{\eta_{tot}} \right) \times 2 \); \( \eta_{tot} = \) total conversion efficiency one usually assumes \( P_0 \ll P_b/\eta_{tot} \) but this must be checked for each type of accelerator.

2. \( D > 1 \) Self-pinching mode - may increase both \( L \) and \( \delta \) by same factor.
   Desired regime of operation (see Ref. 1).

\( D \ll 1 \) Inefficient use of beam.

\( D \gg 1 \) Self-focus unstable - not useful.

3. \( \delta \) formula invalid when critical energy of "beamstrahlung" exceeds nominal beam energy (see Ref. 3) and contributed paper to this workshop by Buon and Coignet.

4. Since \( P_b \) will be closely connected with cost it must be kept as small as possible. For a fixed \( L \) we need to keep \( N \) small to control power. This means one must strive for the smallest possible \( A \).
There are many ways to use these relations depending on the constraints which may be imposed. One rather straightforward way which is useful for illustrative purposes is given by the following algorithm:

1. Choose \( \gamma, L, P_b \) guided by physics needs and your best guess about economics. These choices above determine

\[
f A = \frac{P_b^2}{L} \left( \gamma m_0 c^2 \right)^2
\]

2. The product \( fA \) being now fixed, we might select \( f \) guided by hardware considerations. Now \( A \) and

\[
N = \frac{P_b}{f \gamma m_0 c^2}
\]

are determined.

3. Set \( D = 1 \) (or something slightly larger - no experimental data yet) and determine

\[
\sigma_L = \frac{\gamma AD}{2 \pi r_0 N}
\]

4. Check \( \delta = \frac{4 \pi r_0^3 L \gamma}{3 \sqrt[3]{\sigma_F}} \) If not ok then iterate again.

5. As a measure of the difficulty in producing and focusing the beam described by the above calculations, find the product \( \beta^* \epsilon = A/4 \pi \) and compare with the design value for the SLC, i.e.,

\[
\beta^* = 5 \text{ mm}; \quad \epsilon = \frac{3 \times 10^{-5}}{\gamma} \text{ meter.}
\]

Maintenance of this small emittance in the face of various dilution effects will be a substantial technological challenge.

Some illustrative examples of the product \( fA \) are given in Tables 1 and 2 below. These are not parameters the accelerator will achieve. They are parameters it must be built to achieve. Some of the combinations shown in the tables may be technically impossible.
### Table 1

<table>
<thead>
<tr>
<th>( P_b ) (mW)</th>
<th>1</th>
<th>3</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_b ) (TeV)</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>1</td>
<td>40 * 0.01</td>
<td>350</td>
<td>4000 * 1.0</td>
</tr>
<tr>
<td>10</td>
<td>0.4 * 0.01</td>
<td>3.5</td>
<td>40 * 0.1</td>
</tr>
<tr>
<td>100</td>
<td>4x10^-3</td>
<td>3.5x10^-2</td>
<td>0.4 * 0.01</td>
</tr>
</tbody>
</table>

Numbers with * are ratios of \( A \) required to \( A_{SLC} \) projected to the appropriate \( \gamma \) assuming \( \epsilon \gamma = \text{const} \). Also assumed are \( \beta^* = 5 \text{ mm} \), independent of \( \gamma \), and \( f = 4 \text{ kHz} \).

Note that only in the case of highest beam power and lowest energy and luminosity is the beam area needed as large as that projected for the SLC. The total AC power required for that machine will be

\[
P_{AC} > \frac{10 \text{ MW} \times 2}{\eta_T} = \frac{2 \text{ GW}}{\eta_T(\%)}
\]

One can summarize by saying that if we hope to make significant luminosities at energies significantly higher than now achieved without improbably high capital and power cost we need:
- higher accelerating fields
- less emittance dilution
- higher efficiency
- lower emittance sources
- stronger focusing

in comparison with current technological achievements.

PARTICULAR APPROACHES TO NEW ACCELERATOR DEVICES

A. Near Field Devices

As described in Lawson's introductory discussion of accelerator physics, these devices convert the energy of an EM wave into kinetic energy of beam particles near the surface of conductors (or dielectrics) arranged so that the EM wave velocity equals that of the particle. Four types of device fitting this category were discussed at the workshop.

1. "Normal" Linac

This time honored device is undergoing further development towards optimization for collider use in SLAC, Novosibirsk and by the Japanese Lasertron group. An iris loaded wave guide, manufactured carefully to avoid sparking at high fields is driven by some dc to microwave conversion device such as a klystron, lasertron, gyrocon, etc. operating at $\lambda \leq 10$ cm. So far peak surface fields of 200 MV/m (100 MV/m accelerating) have been achieved. The maximum practical value is not known and will depend on pulse length as well as surface conditions, being higher for shorter pulses. The peak power achieved by Klystrons of the type useful for accelerators is 50 MW with a short pulse conversion efficiency of about 25 percent. The lasertron is expected to be capable of much higher power and efficiency. So far the Japanese group, reporting to this workshop, has achieved 16 kW at $\lambda \sim 10$ cm. Expectations are that lasertron units producing power 100 MW, or much greater, of efficiencies
greater than 80 percent are possible. In addition to the Japanese work there is a lasertron development program at SLAC.

While it has yet to be demonstrated, expectations are that efficiencies of transfer of rf power to beam power of 25 percent may be achieved with derivatives of the traditional linac structure.

The technical challenges faced by developers of the traditional linac are

- measurement of maximum field value
- improved rf-beam energy transfer for collider style beams
- higher power and higher efficiency rf services
- cut component costs
- understanding of scaling laws to find optimum $\lambda$. Note that if we could vary all accelerator parameters ($\epsilon, f, \beta, \ldots$) at will, reducing $\lambda$ helps. There are, however, practical limits which alter scaling to rob us of advantage of reducing $\lambda$ beyond source value. More thought and experiments are needed to understand this.

2. Two-Beam Accelerator

In this scheme the accelerating wave is supported by a loaded wave guide also and the low current, high energy beam being accelerated passes down this wave guide. Parallel to it in the same or in a closely coupled waveguide of special design, the high current, low energy beam which is the basic energy source travels. Its kinetic energy is converted to the wanted EM radiation by free electron laser action, the lost energy being periodically restored by passing the source beam through an induction accelerator unit.

This concept is being pursued by Sessler and coworkers of LBL and LLNL. A prototype FEL operating at $\lambda = 1$ cm has produced about 100 MW peak power into a 1 percent bandwidth.

The technical challenges faced by developers of this approach are;
- high efficiency lasing with reacceleration of the source beam
- suitable accelerating structure matched to the bandwidth of the source and capable of supporting high gradient while providing high rf-beam energy transfer efficiency
- cost estimates for a complete accelerator
- method for accommodating the path length differences between the sinuous source beam and the straight high energy beam.

3. Conducting Droplet Linac

The gradient of the more traditional linacs is certainly limited by spark or melting induced destruction of the conducting surfaces. This limit is expected to be in the 100 to a very few hundred MV/m range. If the near field structure supporting the accelerating wave were disposable after each pulse then this limit might be raised substantially. With this in mind R. Palmer (BNL) has suggested the use of an array of liquid droplets as the near field structure. The droplet array would be produced by modulating the streams from micro nozzles such as those used in ink jet printers. Drive power would come from a laser. The droplets would be made conducting by ionizing their surfaces, perhaps with the driving laser itself. Current thought is to use 10 μ radiation to capitalize on the already extensive developments of high power CO$_2$ lasers. Technical challenges which must be met are;

- formulation of precision droplet streams of 1 μ droplets (required tolerances yet to be studied)
- formation of surface plasma for needed time duration
- development of a suitable feed method for laser to structure coupling
- understanding of beamloading and wake characteristics of the droplet structure.
- demonstration of superior peak field performance
development of a 10 ps laser with high rep rate and good conversion efficiency.

Experiments using a copper grating as the near field structure will begin in 1985 as a collaboration of BNL and NRC and AECL in Canada.

In both the traditional linac two beam accelerator and the droplet accelerator, the accelerating wave is built up resonantly from a relatively narrow band power source. Broadband accelerators are also being studied:

4. Wakefield Accelerators

The kinetic energy of a bunched beam can be converted into broad band electromagnetic field energy in the form of a pulse on a transmission line by passing the beam through a periodic structure. This wake pulse can subsequently be used to accelerate other particles. A form of this accelerator being developed by Voss and Weiland at DESY is termed the Wakefield Transformer. Calculation shows that a low current high energy beam of particles each having 20 or more times the kinetic energy of the high current, low energy source beam particles should be possible. In the DESY device a ring of electrons is formed by laser photo excitation of a ring shaped cathode. The ring is subsequently accelerated in a conventional linac after which it is introduced into the wake field transformer where it gives up most of its energy to the wake fields. The wake energy, deposited near the perimeter of a cylindrical structure, is reflected from the perimeter and travels, in the form of a pulse on a parallel plate, radial transmission line, towards the center, being geometrically compressed as it propagates. The radial compression results in multiplication of the local field in the pulse. It is believed that effective accelerating fields of 100 mV/m or more can be achieved. When the pulse has reached the center, a low current beam pulse, the high energy beam, is shot through on the central axis,
extracting energy from the compressed pulse. At DESY the photo-cathode,
drive linac for ring acceleration, solenoidal ring transport system and
wake field transformer are all under construction for test in 1985.

Some work along similar lines in which an electron beam is used as
the source of wake energy was reported at the workshop by researchers
from the University of Osaka.

Technical challenges for the developers of the wake field transformer
(WFT) are:
- stable ring formation of needed high current by photomodulated
electron gun
- stable acceleration of the high current rings in the driver linac
- stable ring compression
- stable deceleration of the high current rings, in the WFT
- provision of sufficient focusing in high energy beam channel of
  WFT to counteract transverse wake forces due to ring misalignment.

As pointed out some years ago by workers at Novosibirsk, the kinetic
energy of a proton beam such as might be accelerated in one of the big
synchrotrons or storage rings can also be converted to wake energy in a
periodic linac type structure. A following electron beam of lower
current, propagating along the same axis could pick up a fraction of that
total energy. In this coaxial version of the scheme the kinetic energies
of the accelerated and source beam particles will be comparable although
some small multiplication may be effected. (A possible arrangement for
an electron collider driven by such a "proton klystron" is found in a
workshop paper by A. Ruggiero.)

B. Far Field Devices

The only possibility known in this class is the inverse free electron
laser. As far as we know now, synchrotron radiation will limit this
device to about 300 GeV. Perhaps a new idea in the future will show how
to increase the limit.

C. **Media Accelerators**

Of several devices studied the plasma beat-wave genre of Tajima and
Dawson seems most interesting. Both laser and beam excited versions have
been discussed. The laser excited type is most studied and appears to
be the more efficient from our current perspective. In it, a tightly
focused, very short, two frequency, laser pulse organizes a plasma of
carefully controlled density, exciting a longitudinal Langmuir wave cap-
able of accelerating particles. It is predicted that effective acceler-
ating fields of several GV/m can be achieved. The wave generated when
the frequency difference of the two laser beam components is just the
plasma frequency can be made very close to light velocity. In the most
straightforward layout of such an accelerator the laser and particle
beams are coaxial and the phase slip between wave and particle limits each
accelerating stage to lengths of a few meters. In more sophisticated
versions the beams travel at an angle to compensate for the phase slip.
By such means it may be possible to increase the stage length. The most
favorable operating wavelength appears to be in the 0.25 to 10 micron
range. On the basis of limited information, the overall efficiency of
such devices has been estimated to be in the $10^{-3}$ to $10^{-4}$ range.

In separate experiments the existence of the beat wave and the
acceleration of particles by a Langmuir wave has been demonstrated.
Current experimental work concentrates on elucidation of the physics of
the beat wave. To be understood are such questions as;

- how exactly must $\Delta \omega = \omega_p$?
- what is rise time of beat wave?
- what is saturation amplitude of beat wave?
- how long can the coherent wake train be?
- what are competing processes (e.g., stimulated Brillouin scattering; stimulated Raman scattering, etc.)?
- is self-focusing of the laser possible and/or desirable under accelerator conditions?

Experiments to elucidate these issues are now under way at UCLA. Soon to start will be similar experiments at RAL with collaboration from Imperial College and CERN. Work is also being carried out by LANL/WR, NRL/Cornell, FNAL/LANL/Wisconsin collaborations as well as at University of Texas and SLAC. The beam excited version is being studied at UCLA and SLAC.

Should the answers to all these questions turn out satisfactorily from the accelerator point of view there remain the issues of efficiency improvement, the need for short pulse, high efficiency lasers and the multiple scattering of the beam in the plasma.

D. Sources

Possible accelerator optimized sources in the microwave, millimeter, infrared and visible were discussed in conjunction with the various acceleration schemes. In some bands the needed peak powers have been achieved. In no case is the ideal source available today. In the lower frequencies, higher peak powers are still needed. In all frequency bands, there will need to be substantial developments to produce shorter pulse lengths of high coherence with at least multikilohertz repetition rate and good conversion efficiency.

Evidently such sources are needed only for accelerator work at the moment so it will be up to the accelerator community to press for their development.
E. Beam Handling

Common to all the schemes is the need to produce submicron beam spots at the collision point. Only by this means can one hope to achieve needed luminosity at acceptable power levels with the single pass electron linear collider method. Higher brightness beam sources, better control of brightness dilution and tighter focusing methods would all contribute improvement. Particularly helpful would be the development of focusing channels which can accommodate significant energy spreads. Basic to success in all of these will be methods of beam position and distribution measurement and control at the submicron level which can be used with TeV beam energies.

Experiments at the SLC will shed some light on these needs. Other precision beams such as that being readied for NA-34 at CERN could be extended to investigate beam handling and control problems, perhaps even at the 100A level.

CONCLUSION

Good progress in developing the various single pass linac schemes so far mentioned is being made. While one has grounds for being optimistic it is not yet clear that any of these approaches will prove viable in the end. Some may not achieve the required cost effectiveness. Some may prove technically unfeasible. Some may have fundamental flaws not yet seen. Thus there is still plenty of room for completely new ideas about other approaches.

Some of the open questions we have about any of the proposed methods may hide other important questions. Thus it is most important to get on with pursuing the questions we know as soon as possible. Growth of interest in attacking these problems is encouraging. More active interest is needed.
Common to all schemes is the need for improvement in power sources, beam sources, confinement and control. By attacking these early on we can make clearer the full range of constraints on the accelerators themselves.

Progress in experiments over the past two years has been substantial. It is likely that results to be obtained in the next two years will have a profound influence on our understanding of these urgent matters.

* * *

REFERENCES


2) P. Wilson, "High Pulse Power rf Sources for Linear Colliders", 12th International Acc. Conf., FNAL 1983.

Discussion

J. Buon, Orsay

I think you were a little too pessimistic about the highest luminosity case, $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ at 1 TeV, regarding the disruption factor which is obtained from a "reasonable" bunch length. In fact, the disruption factor is inversely proportional to the unperturbed cross-section of the beam at the collision point and without taking into account the pinch effect. This gives a much lower disruption figure. G. Coignet and I have derived relatively reasonable parameters in this case and even at higher luminosity. In the Rubbia case we have 5 TeV with $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ of luminosity, with a bunch length of a few millimetres, a beam power of 10 MW and 10-60 kHz repetition rate, while maintaining a disruption factor of the order of 2.

Answer

I have to apologise. I was just giving an example of how that algorithm can go wrong if you just follow it blindly. I agree that there are reasonable solutions.